

LUCY: NAVIGATING A JUPITER TROJAN TOUR

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In January 2017, NASA selected the Lucy mission to explore six Jupiter Trojan asteroids. These six bodies, remnants of the primordial material that formed the outer planets, were captured in the Sun-Jupiter L4 and L5 Lagrangian regions early in the solar system formation. These particular bodies were chosen because of their diverse spectral properties and the chance to observe up close for the first time two orbiting approximately equal mass binaries, Patroclus and Menoetius. KinetX, Inc. is the primary navigation supplier for the Lucy mission. This paper describes preliminary navigation analyses of the approach phase for each Trojan encounter.

INTRODUCTION

The Lucy mission, led by Principal Investigator Hal Levison of the Southwest Research Institute (SWRI), is the first reconnaissance of the Jupiter Trojan asteroids. The management of Lucy is led by the Goddard Space Flight Center and the spacecraft is to be built by Lockheed Martin. KinetX Aerospace provides the navigation services.

Lucy will visit both the L₄ and L₅ swarms surveying 6 Trojans and one main belt asteroid. The Trojans are not a homogenous population. They have a range of colors or spectral types, all characterized by low albedos, with visible reflectivities of between 0.04% and 0.15%. These objects are remnants of giant planet formation. Better understanding their composition and properties provides a unique opportunity to constrain planet formation and evolution models.

Lucy will survey examples of six Trojans, a C-type Trojan and C-type main belt asteroid, the most common type thought to contain a large amount of carbon, rocks and minerals. It will survey two reddish D-types, thought to possibly have originated in the Kuiper belt and to contain organic compounds with possible water ice in their interior, and three P-types, also thought to be rich in organics also with possible water ice in their interior. It will also visit a near equal mass binary system.

A unique trajectory was discovered which visits this diverse sample of Jupiter Trojans of scientific interest with only one visit to each of the L₄ and L₅ swarms. These targets have a variety of ecliptic inclinations, so the timing of the encounters has to coincide with the arrival of the spacecraft and the targets at the intersection (nodes) of the spacecraft and Trojan orbital planes. This means that the arrival times are not flexible and any delays will be accompanied by a large delta-v penalty.

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Lucy is a very high delta-v mission, with total delta-v for the required deep space maneuvers coming in at 1.678 km/s. There is also a resonance in the six year orbital period of the spacecraft with Jupiter's 12 year period, allowing for the possibility of an extended mission.

A critical aspect of achieving the required accuracy for the Lucy flybys is optical navigation (OpNav). Using only ground-based observations of the Jupiter Trojans would require greater flyby distances. OpNav images taken from the spacecraft are used to more accurately determine the trajectory of the Trojan relative to the spacecraft allowing lower flyby closest approach distances. Two of the imagers on board the Lucy spacecraft have heritage from the New Horizons mission to the Pluto system and the Kuiper belt. The L'LORRI long-range reconnaissance imager from the Johns Hopkins University Applied Physics Laboratory (APL) to be flown on Lucy is "nearly a clone" of the New Horizons LORRI imager, which was successfully used as the primary OpNav camera. Also flying on Lucy is the L'Ralph multispectral visible and near infrared spectrometer, which also is the New Horizons Ralph instrument which has been optimized for Trojan science. The MVIC imager on the L'Ralph instrument was successfully used on the New Horizons approach to the Pluto system as the backup OpNav camera.

THE LUCY TRAJECTORY

Scheduled to launch on October 16, 2021, Lucy will perform 9 flybys in total, consisting of three Earth gravity assists, six asteroid encounters and five deep space maneuvers, four of them quite large. Lucy's L₄ encounter trajectory is highly elliptical, with an eccentricity of 0.7, an ecliptic inclination of between 4-5 degrees, and a period of six years. Two Earth flybys and two deep space maneuvers (DSMs) alter the trajectory to encounter the first target, main belt asteroid Donaldjohanson, while a third DSM puts the spacecraft on course to the Jupiter L₄ swarm. A timeline of mission events is shown in Figure 1. Note that all four Trojan encounters in the L₄ swarm occur within a span of 15 months.

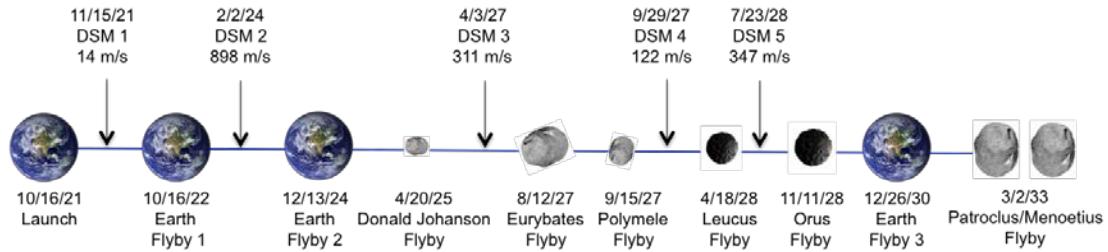


Figure 1. Lucy Timeline.

As the spacecraft orbit is in an approximate 2:1 resonance with Jupiter's orbit, and as a complement to Figure 1, it is convenient to visualize the mission in a frame which rotates with Jupiter, as shown in Figure 2.

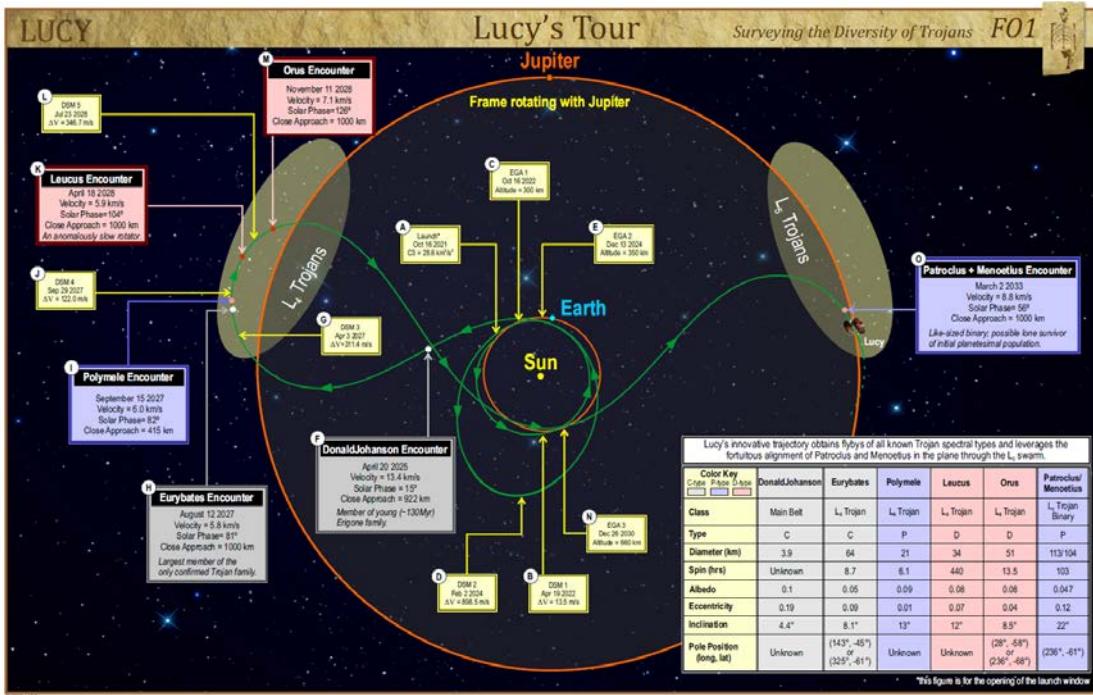


Figure 2. Lucy Overview, 6 Encounters, 3 Earth Flybys, and 5 Deep Space Maneuvers.

One month after launch is the mission's first deep space maneuver, a relatively small 14 m/s which is largely a timing maneuver to position the trajectory properly for the first Earth gravity assist (EGA-1) one year after launch. This flyby serves primarily to increase the semi-major axis, increasing the period to just over two years and providing a small, 0.19 degree, inclination change.

Fourteen months following EGA-1 is the largest DSM of the mission, DSM-2, at 898 m/s, which makes changes to the orbit plane and shape, and slightly decreases the period to properly position the spacecraft for EGA-2. EGA-2 puts the spacecraft into a trajectory which intersects that of the first target, 52246 Donaldjohanson. Donaldjohanson is a main belt, C-type asteroid, named after the co-discoverer of the Lucy hominoid fossil, American paleontologist Donald Johanson. While of scientific interest in itself, the team will use the April 20, 2025 encounter with Donaldjohanson as a dry-run of the subsequent Jupiter Trojan encounters. Specifically for navigation, it will be the mission's first test of the OpNav system on a faint target, with a diameter of less than 4 km, an albedo of 0.1 and a small solar phase angle of 8 degrees. The flyby radius of closest approach is 1000 km, as it is for every mission target except Polymele. Donaldjohanson is the only encounter where the spacecraft and asteroid orbital planes are roughly co-planar. Table 1 shows the Lucy trajectory classical, ecliptic orbital elements, and Table 2 shows the Trojan target classical elements and selected physical parameters relevant to navigation on the approach. The most significant changes are highlighted in red for clarity.

Table 1. Significant Mission Events and Associated Heliocentric Ecliptic Classical Elements

Event Date	Launch	DSM-1	EGA-1	DSM-2	EGA-2	DSM-3	DSM-4	DSM-5	EGA-3
	16 Oct 21	15 Nov 21	16 Oct 22	2 Feb 24	13 Dec 24	3 Apr 27	29 Sep 27	23 Jul 28	26 Dec 30
Δv [m/s]	-	14	-	898	-	311	122	347	-
h_p [km]	-	-	298	-	347	-	-	-	640
a [au]	1.00	1.00	1.63	1.55	3.36	3.31	3.30	3.32	3.30
e	0.16	0.16	0.39	0.45	0.71	0.73	0.73	0.73	0.71
i [deg]	0.21	0.21	0.02	0.01	4.41	4.98	4.56	1.83	10.74
Ω [deg]	23.22	23.24	27.05	253.77	261.21	257.51	259.39	274.72	274.70
ω [deg]	261.51	261.48	354.21	132.16	160.45	162.88	161.26	145.54	155.91
T [years]	1.00	1.00	2.09	1.93	6.14	6.01	5.99	6.04	6.00
Next Encounter	EGA-1	EGA-1	EGA-2	EGA-2	DJ	Eury/Poly	Leucus	Orus	Patroclus

Table 2. Lucy Trojan Target Ecliptic Classical Elements and Selected Physical Parameters

	Donald Johanson	Eurybates	Polymele	Leucus	Orus	Patroclus
a [au]	2.384	5.190	5.164	5.285	5.128	5.217
e	0.186	0.089	0.094	0.063	0.356	0.138
i [deg]	4.419	8.060	12.992	11.558	8.468	22.047
Ω [deg]	262.851	43.551	50.329	251.088	258.561	44.355
ω [deg]	213.000	28.031	4.885	161.201	180.461	308.373
T [years]	3.681	11.825	11.736	12.150	11.611	11.917
Diameter [km]	3.895	63.885	21.075	34.155	50.810	140.362
Albedo	0.10	0.05	0.09	0.08	0.08	0.05
Solar Phase [deg]	8	76	78	100	121	52

Almost two years following the Donaldjohanson encounter, DSM-3 is scheduled on April 3, 2027 to change the spacecraft inclination to 4.98 degrees in preparation for the Eurybates and Polymele encounters. The first Trojan encounter is 3548 Eurybates on August 12, 2027, a 64 km diameter C-type object, followed 34 days later by the 21 km diameter P-type object, Polymele, on September 15, 2027. Both of these encounters have solar phase angles of between 76 – 78 degrees on approach. The Polymele encounter poses particular challenges from a navigator’s point of view. Not only is it a small, dim object at a high solar phase, it occurs only 34 days following the Eurybates encounter. A primary objective is to determine Polymele’s mass to within 25%, which necessitates flying closer than the other Trojan targets, with a closest approach radius of 399 km.

Fourteen days after the Polymele encounter, Lucy will perform DSM-4, an inclination decrease of 0.42 degrees to 4.56 degrees, to target the first of two D-type asteroids, 11351 Leucus on April 18, 2028. Leucus is unique among the Trojan’s visited by Lucy as it has a very long rotational period of 447 days. It has an albedo of 0.08 and is only 34 km in diameter with an approach solar phase angle of 100 degrees, so it will be a challenge for the OpNav system with less than $\frac{1}{2}$ of the body lit.

Three months after the Leucus encounter, DSM-5, the second-largest maneuver of the mission, is performed to change the inclination from 4.56 to 1.83 degrees, and rotate the orbital plane by a 15 degrees. This will alter the trajectory to intersect that of the final target in the L₄ tour, D-type 21900 Orus on November 11, 2028. Orus has a diameter of 51 km, an albedo of 0.08, and an approach solar phase angle of 121 degrees, which is the largest of the mission. This is one of the more challenging flybys for the OpNav system, as is discussed further in the OpNav section.

Following the Orus encounter as the spacecraft's highly elliptical trajectory takes it back toward the inner solar system. No further DSM's are required before the 3rd Earth flyby, EGA-3, on December 26, 2030. EGA-3 changes the inclination by nearly 9 degrees from 1.83 to 10.74, to put the spacecraft on course to encounter the Patroclus-Menoetius nearly equal mass binary in the L₅ swarm.

The PM-binary system has the distinction of having the largest inclination of the Lucy Trojan targets at 22 degrees. These bodies are the largest of the Lucy Trojan tour with Patroclus having a diameter of 113 km, with a solar phase angle on approach of 52 degrees but a low albedo of 0.05. This system requires the navigation team to produce an ephemeris for both Patroclus and Menoetius orbiting their common center of mass, as well as a trajectory for the center of mass of the system orbiting the Sun.

TROJAN A PRIORI EPHEMERIDES⁵

A-priori ephemerides play an important role in navigating to a small body. Current plans for observing the Lucy Jupiter Trojans are to have 100 observations per year until the Lucy encounter. To more accurately model the Trojan uncertainties, a covariance analysis was performed by the JPL Solar System Dynamics group to provide the navigation team updated covariances more representative of what we can expect leading up to the encounters using the proposed observing schedule, assuming each object is observable with an accuracy of 0.5 seconds of arc, equivalent to 2.4 μ rad, or about $\frac{1}{2}$ of a L'LORRI pixel. Covariances were provided to the navigation team with epochs of January 1, 2025 for the Donald Johanson encounter, January 1, 2027 for the Eurybates, Polymele, Leucus and Orus encounters, and January 1, 2032 for the Patroclus encounter.

The internal format of the covariances used by the navigation software is in Brouwer/Clemence Set III elements. It is useful to generate an error ellipse in a system which is easier to visualize. One way to do this accurately is to use the navigation software and the covariance analysis setup to produce an error ellipse in any of the coordinate systems allowed by the navigation software. To avoid having extraneous uncertainties in the results below, the covariance analysis is run estimating only the spacecraft position and velocity, and the Trojan Set III elements. The spacecraft position and velocity a priori uncertainties are set to zero, and all of the simulated data is deleted. This leaves only the Trojan uncertainties in the problem

The results are given in Table 3, which shows the a-priori Trojan ephemeris uncertainties relative to the Sun, and those of Lucy relative to the Trojan due to the Trojan ephemeris uncertainty, mapped to the encounter closest approach time. The coordinate system chosen is the View 1 system, also commonly referred to as the Plane of Sky or RTN (Radial, Transverse and Normal) systems. Results are given for the Trojan relative to the Sun and the spacecraft relative to the Trojan.

Table 3. Trojan A-priori Ephemeris Uncertainties in the View 1 / Plane of Sky / RTN System.

Trojan APSIGs	View 1 Trojan wrt Sun [km]			View 1 SC wrt Trojan [km]			
	R	HxR	H	R	HxR	H	Magnitude
Eurybates	186	548	306	155	547	324	654
Polymele	111	542	246	118	518	293	607
Leucus	237	725	369	366	662	382	847
Orus	193	734	308	538	529	318	819
Patroclus	157	541	247	274	448	320	615

⁵ Ephemerides and covariances provided by the JPL Solar System Dynamics group.

The large radial uncertainties make clear that OpNav is required for Lucy. While these uncertainties may improve with the introduction of the GAIA star catalog, a number of factors can cause the center of brightness to be different from the center of mass of the targets. These include: center-finding uncertainties due to the uncertain shape of the Trojans, lighting conditions, and variable albedo. These are the dominant error sources and will limit the accuracy of the astrometry. Encounter navigation requirements are discussed later in the paper.

NAVIGATION SYSTEM

The objective of the Lucy navigation system is to determine the trajectory of the spacecraft relative to the Earth and the encounter target, and to control the trajectory to achieve the desired flyby state in order to meet science objectives.

Measurement Subsystem

During the cruise phase, the orbit determination process uses Doppler, ranging and Delta-Differential One-Way Range (DDOR) data from the Deep Space Network (DSN) to determine the spacecraft trajectory relative to the Earth. Doppler data provides a direct measurement of the line-of-sight velocity relative to the DSN tracking antenna, accurate to about 0.1 mm/s. Ranging data provides a direct measurement of the line-of-sight distance from the DSN antenna to the spacecraft. It is not as accurate as the integrated Doppler data type, but is used to augment the Doppler data and provides the constant of integration necessary to fix the position of the spacecraft relative to the Earth.

The Trojan encounters require a precise target-relative navigation measurement. Using the on-board L'LORRI camera, optical images will be carefully sequenced to provide this relative navigation information. These OpNav images not only allow estimation of the Trojan ephemerides, but they also provide cross line-of-sight information to de-correlate the spacecraft state and target ephemerides in the data. For Lucy, OpNav plays a crucial role in navigation and operations. The navigation precision required to achieve the mission science objectives is possible only with the addition of optical data to the radio orbit determination solution. Due to the importance of OpNav for Lucy, it is discussed in greater detail later in the paper.

Delta-Differential One-Way Range

The DDOR data type is formed by differencing two Very Long Baseline Interferometric (VLBI) measurements⁶ between a spacecraft tone signal and one or more nearby quasars whose positions are known to high accuracy. The VLBI measurement determines the spacecraft offset from the baseline formed by two DSN antennas, and provides a direct measurement of the spacecraft angular offset relative to the baseline. To obtain a measurement, both DSN antennas slew to point at a quasar, take data for approximately 10 minutes, then slew to the spacecraft for approximately 12 minutes, and then back to the quasar for another 10 minutes, forming a Q-S-Q sequence. This VLBI data is then differenced to form the DDOR data type. The measurements are subject to a variety of error sources, including troposphere and ionosphere effects as well as station-dependent parameters. Differencing the VLBI measurements provides cancellation of the common error sources. The accuracy of the DDOR measurement is approximately 2 nanoradians, which is equivalent to 0.3 km at 1 AU. Typically for station elevations above 10 degrees, two DDOR data points are acquired during each observing session. When one or both of the stations are below 10 degrees elevation, the observations are of degraded accuracy and often only one DDOR data point is obtained.

⁶ See Appendix A for a geometric diagram of the VLBI measurement.

Using two VLBI baselines orthogonal to one another provides angular position of the spacecraft in the two dimensions of the plane of the sky, normal to the line-of-sight measurements provided by Doppler and range data. DDOR has been in use by the Lucy navigation team on both the Messenger and New Horizons missions since 2004 with the first Venus flyby for Messenger. It has been proven to make a significant contribution to the accuracy of the navigation system.

The Trojan targets for Lucy all have declinations below -19 degrees during the encounter phase. This creates problems for the acquisition of VLBI measurements on the East-West baseline, used to create the DDOR measurements, since they require spacecraft equatorial elevations of greater than 10 degrees at each station for 40 - 60 minutes. Using DSN stations, this can be a problem for low spacecraft geocentric equatorial declinations on the East-West baseline. East-West baseline DDOR measurements are not possible for declinations less than -25 degrees. It is evident that DDOR data on the East-West baseline will be of degraded accuracy, and for the Patroclus encounter with a declination of -27 degrees during the approach, East-West DDOR will be unavailable when using DSN stations. It is possible to get DDOR for any place in the sky if necessary using ESA or JAXA. This discussion is left to a later paper. Table 4 below shows the encounter declination and expected DDOR accuracy.⁷

Table 4. Lucy Approach East-West Baseline DDOR Availability

Trojan	Declination [deg]	# DDOR points	X-band data weight [1 σ]
Donald Johanson	8	3	0.06 ns
Eurybates	-19	2	0.12 ns
Polymele	-19	2	0.12 ns
Leucus	-24	1	0.25 ns
Orus	-22	2	0.20 ns
Patroclus	-27	0	N/A

COVARIANCE ANALYSIS

Accurate delivery and knowledge of spacecraft position and timing are essential to meet the science objectives of the mission. The current requirements for the Flight Dynamics System (FDS), as defined in the Mission Requirements Document (MRD)⁷, are summarized in Table 5. Note that the smallest body, Polymele, is called out specifically and provides arguably the most challenging requirement for delivery among all of the planned Trojan encounters. As part of the on-going evolution of the mission plan, targeted distances and precise target locations may need to be adjusted to avoid collision with satellites, rings or other obstacles that may be detected well in advance from ground observations or later during final approach.

⁷ Emails with Jim Border of JPL.

Table 5. Delivery and Knowledge Requirements for Flight Dynamics System (FDS)

Name	Description	Rationale
Target Distance for Polymele	Lucy navigation shall deliver the spacecraft to a C/A distance within 474 km for Polymele with 3σ uncertainty.	Modeled performance shows that for the smallest target (Polymele), for an estimated density of 1g/cc, in order to determine the mass to 25% accuracy, the spacecraft needs to fly within a distance of 474 km to have an accurate measurement of the Doppler shift, in addition to a post flyby reconstruction accuracy of better than 1.5 km (1σ).
Nominal Target Distances	Lucy navigation shall target nominal closest approach distances as specified in the Mission Plan.	Required to meet resolution requirements and to give enough time at close enough distance for redundant observations to account for an auto-recovery.
On-Board Ephemeris Accuracy in Space and Time	Lucy navigation shall support a knowledge update to the Trojan ephemeris with an OD cut-off 5 days prior to the C/A with a 3σ maximum uncertainty of: <ul style="list-style-type: none"> • B-Plane (radius): 50 km* • Time of Flight: 200 s* 	Bounds the pointing errors on approach, to size camera appropriately.
Target Distance Uncertainty	Lucy navigation shall deliver the spacecraft to a C/A distance with less than 75 km, 3σ .	Modeled performance shows that for the smallest target (Polymele), for an estimated density of 1g/cc, in order to determine the mass to 25% accuracy, the spacecraft needs to fly within a distance of 474 km to have an accurate measurement of the Doppler shift, in addition to a post flyby radial reconstruction accuracy of better than 1.5 km, 1σ , 5.0 km for Patroclus/Menoetius.

* Values indicated are subject to be revised (TBR).

In order to assess the Lucy navigation performance, a detailed covariance analysis was performed for each target body to determine the navigation errors as a function of time from the encounter. This analysis included all of the error sources that affect navigation accuracy and the data acquisition strategy that is currently planned. During the approach to each Lucy target, the spacecraft orbit determination error relative to the target is a statistical combination of the error of the spacecraft relative to the Earth and the Trojan ephemeris error.

The transition from cruise phase begins 60 days from the encounter (E-60), where Doppler and ranging data are acquired in three 8-hr passes per week. Three OpNav sessions are scheduled per week. It is anticipated that L'LORRI 4x4 imaging will be necessary from E-60 to E-45 due to low target magnitudes. DDOR is assumed to be acquired for both the North-South and East-West baselines in two sessions per week.

Beginning 45 days prior to the encounter, the plan is to begin acquiring OpNav images daily. As was shown in the L'LORRI analysis, we also expect to be able to utilize the higher fidelity L'LORRI 1x1 mode at this time. This tracking schedule will continue until E – 10 days, when continuous DSN tracking will be available and DDOR observations will be discontinued.

A typical Lucy Trojan encounter timeline is shown in Figure 3.

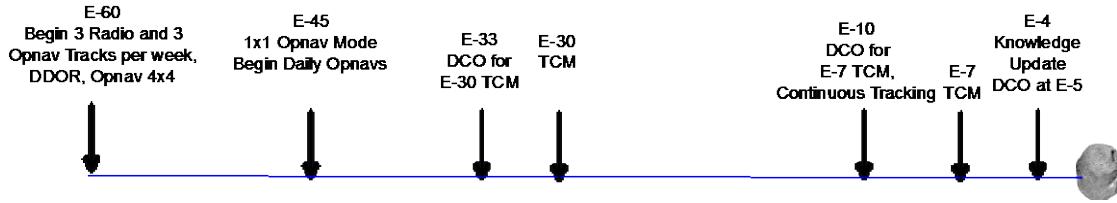


Figure 3. Typical encounter timeline

Trajectory correction maneuvers (TCMs) are currently planned at E – 30 days and E – 7 days, with tracking data cutoffs for the orbit determination solutions used in the TCM planning three days prior to each maneuver, at E – 33 days and E – 10 days, respectively.

Modeling assumptions for the covariance analysis are given in Table 6.

Table 6. Baseline Covariance Analysis Assumptions

Estimated Parameters	A-priori Uncertainty
Spacecraft State	200 km, 30 m/s
Solar pressure	10% Effective cross section 70 m ²
Stochastic acceleration	1.0 x 10 ⁻¹² km/s, 1 σ white noise 1 day batch size
Maneuver Execution Errors	30 mm/s + 4% of magnitude (0.5 m/s), 3 σ
Commanded Momentum Dumps	0.4 mm/s, 3 σ ,
Planetary and Small Body Ephemerides	DE421, Trojans with correlated covariances provided by JPL Solar System Dynamics group. Future Trojan tracking assumes 100 obs/year at 0.5 arc seconds, or 2.4 microradian accuracy (1/2 L'LORRI pixel).
Consider Parameters	A-priori Uncertainty
Station locations	0.5 m
UT1 and polar motion	15 cm, 10 cm
Troposphere (wet and dry)	4 cm, 1 cm
Ionosphere (day and night)	5 cm, 1 cm
Data Type	Data Weight
2-Way Doppler	0.1 mm/s
2-Way Range	100 m
OpNav (L'LORRI)	4 pixels E-60 to E-45, 1 pixel after E-45
DDOR	0.2 ns

The data arc begins 60 days before each encounter. The data weights are 0.1 mm/s for Doppler, 100 m for range, 0.2 ns for DDOR, and 4 pixels for OpNav from E-60 to E-45, and 1 pixel afterward. Commanded momentum dumps are assumed to occur every 4 days, with an uncertainty of

0.4 mm/s on each axis. The estimated parameters include the spacecraft state, solar pressure, commanded momentum dumps, and TCMs on approach. A white noise stochastic acceleration is also included to account for modeling errors. It has magnitude of 1×10^{-12} km/s² with a time between updates of one day. The uncertainties for the maneuvers at E-30 and E-7 days are 30 mm/s + 4% of the magnitude, which is assumed to be 0.5 m/s. The solar pressure model assumes a spacecraft with a 70 m cross sectional area, pointed at the Sun.

The delivery uncertainty is the uncertainty that the spacecraft is “delivered” to the target. It is based on a tracking data cutoff of E – 10 days. A TCM, with its associated maneuver execution error, occurs at E – 7 days. Delivery uncertainties in the B-plane⁸ are shown in Table 7.

Table 7. Covariance Analysis Delivery Uncertainties at Closest Approach

Body	Time of Closest Approach	Penumbra Radius [km]	Uncertainties at Closest Approach [3- σ]					
			B.R [km]	B.T [km]	LFT [s]	VxH [km]	V [km]	H [km]
Eurybates	12-AUG-2027 01:50:35.156736850 UTC	1000	32	31	68	29	392	33
Polymele	15-SEP-2027 10:07:44.197310090 UTC	399	42	35	75	36	450	41
Leucus	18-APR-2028 18:34:04.156152963 UTC	1000	56	49	64	33	378	67
Orus	11-NOV-2028 18:11:55.299177408 UTC	1000	53	45	22	37	158	59
Patroclus	02-MAR-2033 23:22:08.186630249 UTC	994	47	52	23	51	199	48
								211

* Tracking data cutoff at Encounter – 10 Days

Plots of the delivery uncertainties for Eurybates are given in Figure 4. On the left are plots of the error ellipse as the spacecraft intercepts the B-plane. The black ‘+’ indicates the center of the target body, while the black circle around it is a circle represents the target body diameter. The spacecraft B-plane intercept is given as the blue ‘+’ with its blue error ellipse surrounding the intercept. The red circle around the SC intercept is the radial requirement of 75 km. To the left of the B-plane plot is the time of flight uncertainty. On the right in Figure 4 are plots of the time history of the spacecraft B-plane uncertainties on approach. These plots use tracking data up until the time indicated, compute a solution and uncertainty, and map to the closest approach time. No data is included in the solution after E – 10 days. Delivery uncertainty plots for Polymele, Leucus, Orus and Patroclus are given in Figures 5-8.

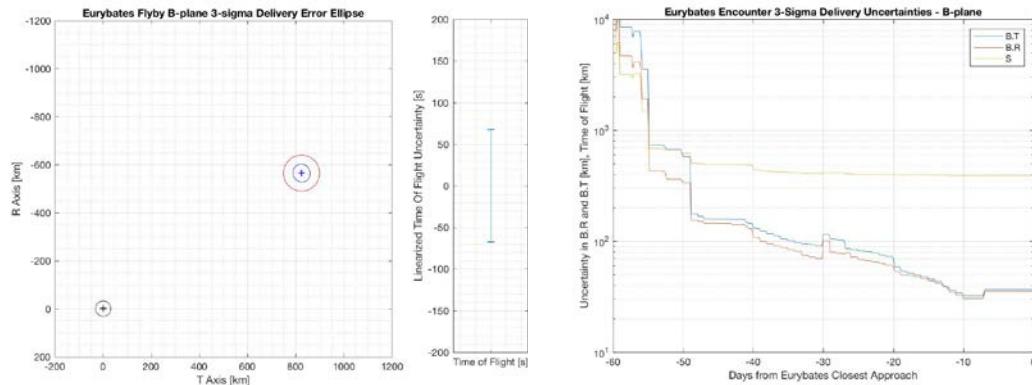


Figure 4. Eurybates Encounter 3 σ Delivery Uncertainties

⁸ See Appendix B for a diagram of the B-plane.

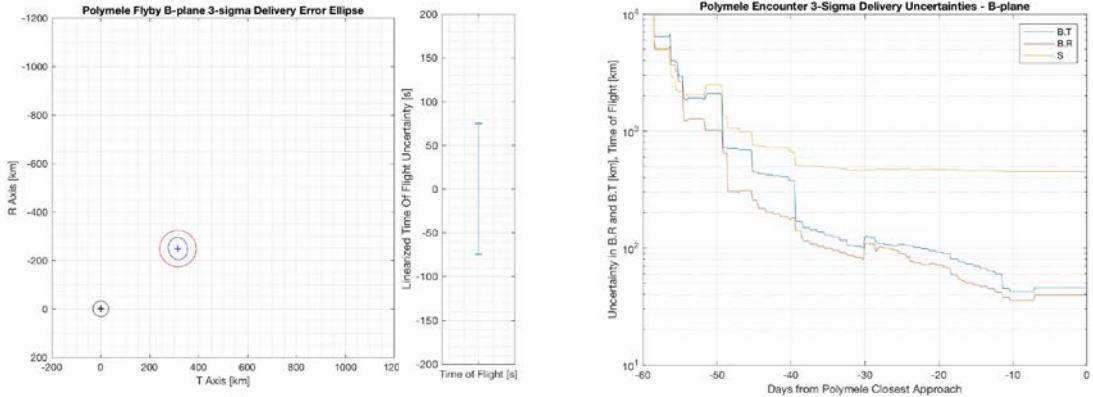


Figure 5. Polymele Encounter 3σ Delivery Uncertainties.

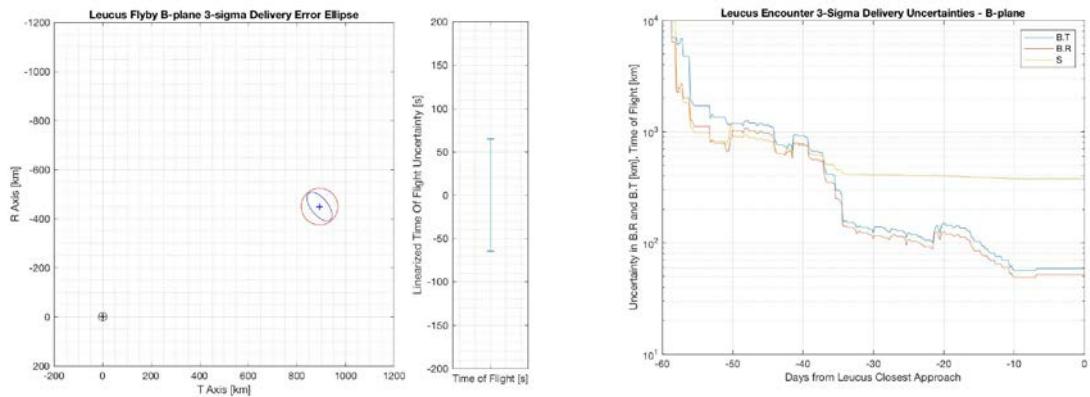


Figure 6. Leucus Encounter 3σ Delivery Uncertainties.

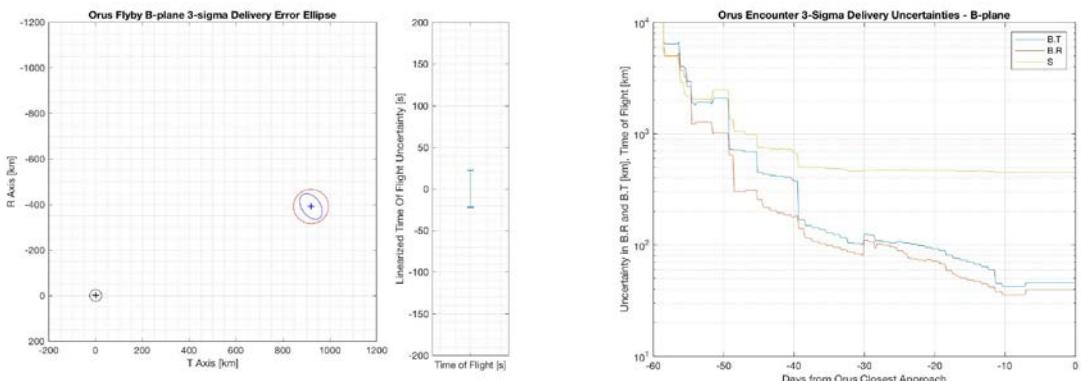


Figure 7. Orus Encounter 3σ Delivery Uncertainties.

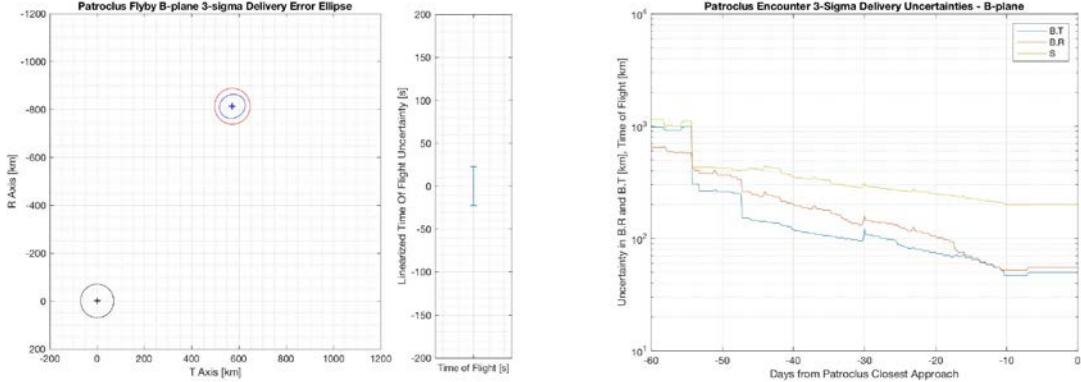


Figure 8. Patroclus Encounter 3σ Delivery Uncertainties.

The last chance to change the trajectory in the nominal encounter sequence is the TCM at E – 7 days. However, tracking data continues to be acquired. While it is too late to make a trajectory correction at this point, spacecraft pointing can be adjusted based on the current best trajectory knowledge to correct for possible ephemeris errors in the current onboard solution. This could be caused by a TCM execution error, or because OpNav solutions, which become more powerful the closer the spacecraft is to the target, indicate that the current on-board trajectory has an error which could affect the flyby science data acquisition.

Knowledge uncertainty describes the uncertainty at E – 4 days, based on a tracking data cutoff of E – 5 days. A Knowledge Update refers to providing the spacecraft with an updated spacecraft ephemeris based on the improved trajectory knowledge. The last planned knowledge update for Lucy is planned for E – 4 days. Table 8 shows the knowledge uncertainties at E – 4 days.

Table 8. Covariance Analysis Knowledge Uncertainties at E – 4 Days

Body	Time of Closest Approach	Periapsis Radius [km]	Uncertainties at E-4 Days [3- σ]						
			B.R [km]	B.T [km]	LFT [s]	VxH [km]	V [km]	H [km]	Mag [km]
Eurybates	12-AUG-2027 01:50:35.156736850 UTC	1000	31	23	69	20	396	23	397
Polymele	15-SEP-2027 10:07:44.197310090 UTC	399	30	32	73	25	438	25	439
Ieucus	18-APR-2028 18:34:04.156152963 UTC	1000	48	34	63	20	370	40	373
Orus	11-NOV-2028 18:11:55.299177408 UTC	1000	40	35	22	25	153	33	158
Patroclus	02-MAR-2033 23:22:08.186630249 UTC	994	45	49	25	43	204	33	212

* Tracking data cutoff at Encounter – 5 Days

In a trajectory reconstruction, all of the tracking data before, during and after the flyby is used to create an accurate post-encounter flyby trajectory. This data is used for the post-flyby analysis of the science data, including possible mass determination for Polymele. In Table 9, the OD filter computes a solution using data through E + 10 days, then computes B-plane intercept and associated uncertainties, and maps the uncertainties back to the time of closest approach.

Table 9. Covariance Analysis Reconstruction Uncertainties at Closest Approach

Body	Time of Closest Approach	Periapsis Radius [km]	Uncertainties at Closest Approach [3- σ]						
			B.R [km]	B.T [km]	LFT [s]	VxH [km]	V [km]	H [km]	Mag [km]
Eurybates	12-AUG-2027 01:50:35.156736850 UTC	1000	2.50	3.90	31.23	4.53	180.65	0.95	180.71
Polymele	15-SEP-2027 10:07:44.197310090 UTC	399	3.57	3.16	102.96	3.10	620.58	3.62	620.60
Ieucus	18-APR-2028 18:34:04.156152963 UTC	1000	1.84	2.52	51.58	2.58	302.58	1.76	302.59
Orus	11-NOV-2028 18:11:55.299177408 UTC	1000	2.13	2.16	20.19	2.17	144.14	2.11	144.18
Patroclus	02-MAR-2033 23:22:08.186630249 UTC	994	4.86	3.50	13.87	5.98	122.37	0.30	122.52

These results indicate that with current assumptions, the 75 km 3σ radial delivery requirement is met for each encounter, in accordance with Table 5.

OPTICAL NAVIGATION

OpNav images augment the radiometric data on approach by measuring the angular offset between the center of the Trojan against the star background. Radiometric data, including Doppler, ranging and DDOR measurements, provide measurements of the spacecraft relative to the Earth both along and normal to the line of sight. OpNav provides measurements of the spacecraft relative to the target, whose position is only known from ground and/or Hubble based measurements a priori. With OpNav, the relative position and predicted target b-plane intercept can be estimated with more accuracy than with Doppler, ranging and DDOR alone. OpNav ties the spacecraft to the target, whereas the other measurement types tie the spacecraft to the Earth.

The Lucy mission is characterized by small targets with low reflectivities (albedos), most at large solar phase angles, resulting in faint target magnitudes. Techniques to mitigate this and acquire the target as early as possible require either longer exposure times or a technique called co-adding, both of which have their own challenges. The exposure times for the Trojan targets and the star background must be long enough to over expose the dim objects, but not so long that the camera pointing drift results in image smear.

Co-adding images is a process that involves registering (superimposing) a set of images together and summing the target signal intensity from each image in order to produce a final “co-added” image with a higher signal to noise ratio (SNR) than any single image. When producing a co-added or “stacked” image for OpNav, all images in the set need to be acquired at nearly identical times to ensure that the apparent spacecraft to target angle does not change from image to image. Using this assumption, the set of images can be registered together using the background stars in the field, and the signal intensity in all the images can be summed together to produce one co-added image. The centroid of the target in this final co-added image can be calculated and sent to the orbit determination filter as a single optical observable (one approximate image epoch, camera attitude, and set of pixel/line coordinates).

Lighting conditions, geometric shape of the target, albedo variations and many other considerations may cause the calculated optical center to be different than the true geometric center of the target. As a result, this raw “center-of-brightness” may need to be corrected in order to shift pixel/line coordinates to the “center-of-figure” estimate. The center-of-figure represents the center of the 2D shape projected onto the image plane (including dark regions). This “center-of-figure” is then also assumed to be the center of mass for the target.

Since centroiding and/or modeling errors exist in all of these calculations/assumptions, the effect of these potential issues is important to understand in order to assess the expected navigation performance.

The Opnav system used by the Lucy navigation team was developed, tested and validated on the New Horizons mission during the Pluto cruise phase, before it was exercised during the Pluto encounter. It is also being used on the OSIRIS-REx mission. Due to the complex nature of faint target astrometry, the capability to construct and process co-added images is currently being developed and will be tested using the L’LORRI camera on New Horizons during the approach to Kuiper Belt object 2014MU69.

OpNav Performance Simulation For Leucus and Orus

An analysis was performed simulating the OpNav performance for Leucus and Orus, whose small sizes, low reflectivity and high phase angles, 100 and 121 deg respectively, provide for one of the more challenging encounters for Lucy. The simulation uses a priori shape models provided by Simon Marchi of SWRI, the Lucy Deputy Project Scientist.

The objective was to simulate an image using a known shape model and use the OpNav software to determine the center-finding error. The images were assumed to have been taken 10 days before each encounter. The simulation conditions assumed a Trojan absolute magnitude of 10. A phase coefficient, how the magnitude varies with solar phase angle, of 0.04 mag/deg was assumed, along with Trojan albedos of 0.08. L'LORRI camera parameters, including a noise model, were used. The star catalog is UCAC4.

Each image was processed through the KXIMP star-based navigation software, and used the following center-finding techniques:

- Cross-correlation of simulated sub-pixel images, assuming knowledge of the shape. The dominant error source using this method is image noise. This represents the lower bound of capability.
- Least squares estimate of the two-dimensional point spread function (PSF). The dominant error source using this method is the center of brightness bias.
- Least squares estimate of the two-dimensional point spread function with a correction for the center of brightness using the Lommel-Selliger scattering law. This is the most realistic case assuming poor a priori knowledge of the shape and surface scattering properties.

Figure 5 shows the simulated OpNav images and Figure 6 shows the center-finding results.

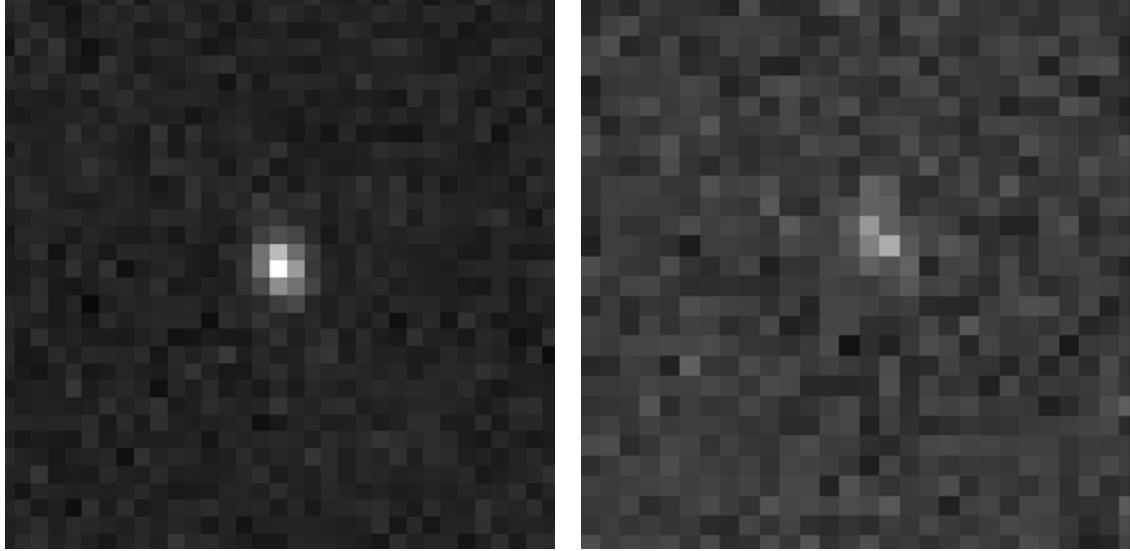


Figure 5. Simulated OpNav Images of Leucus (left) and Orus (right) at Encounter – 10 days.

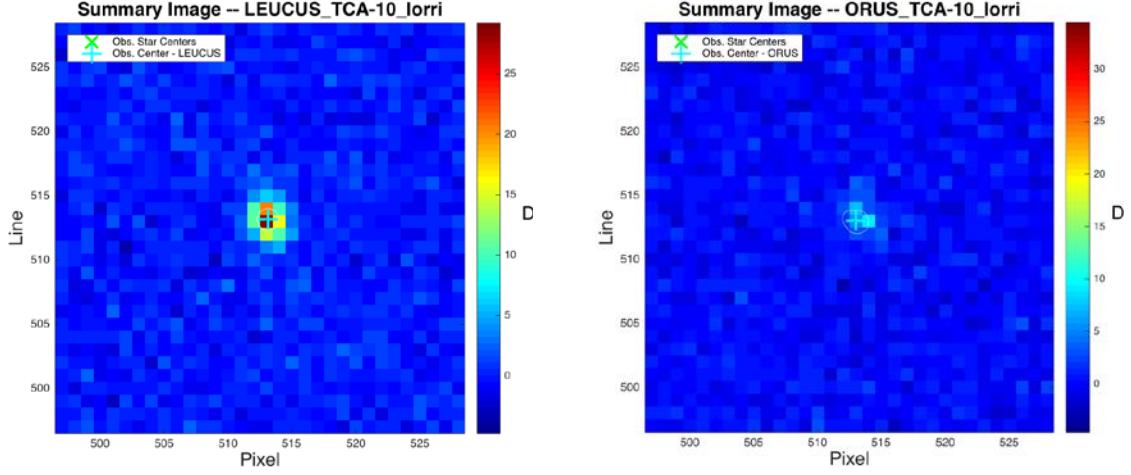


Figure 6. Leucus and Orus Centerfinding Results

The results of the simulation are tabulated in Table 10. These results demonstrate the center-finding capability for irregular shaped, high phase objects is meets Navigation covariance assumptions of 1 pixel error, with margin.

Table 10. OpNav Simulation Results

Target	Technique	Pixel Error [px]	Line Error [px]	Mag Error [px]
Leucus	1	0.022	0.081	0.084
	2	0.118	0.158	0.198
	3	-0.128	0.051	0.138
Orus	1	0	0.039	0.039
	2	0.498	0.396	0.636
	3	0.191	0.258	0.321

L'LORRI Camera Performance

An analysis was performed using Polymele and Orus to determine when it will be possible to use the L'LORRI camera's CCD 1x1 mode. This is a function of the brightness of the object, and the received signal to noise ratio. Both longer exposure times and using the "co-adding" technique were considered.

The L'LORRI analysis assumes a single 5 second exposure for each CCD format, and finds the visual magnitude (V-mag) limit that gives a SNR of 7. Using the co-adding technique, 50 exposures are assumed. Three CCD formats were considered, 1 x 1, 2 x 2 and 4 x 4 modes, where in the 2 x 2 case, four pixels are combined into a single "pixel", and for 4x4 mode, 16 pixels are combined into a single "pixel" measurement. Two cases for platform stability were analyzed. The first, an ideal case, takes no account of pointing stability. The second case is the "degraded" case, where the pointing stability is represented by a convolution of the L'LORRI point spread function

(PSF) with a two dimensional Gaussian whose sigma is 5 micro-radians, or 1 pixel for the L'LORRI camera.

To calculate the visual magnitudes for Orus and Polymele, the current best estimates for the body sizes and geometric albedos were used, with a linear phase law of 0.04 mag/deg. The geometry of the observations (i.e., range to target, heliocentric distance, and phase angle) was determined from ephemeris files from the JPL Solar System Dynamics group. Results for the optimistic case of perfect pointing stability are given in Table 11.

Table 11. L'LORRI Camera Performance Optimistic Case – Perfect Pointing Stability

CCD Format	V-mag 1 x 5s	Orus (days before CA)	Polymele (days before CA)	V-mag 50 x 5s	Orus (days before CA)	Polymele (days before CA)
1x1	16.05	69	70	18.17	> 184	> 184
2x2	16.70	96	97	18.82	> 184	> 184
4x4	16.88	106	107	19.00	> 184	> 184

Table 12 shows results for the "Degraded" case, when the pointing stability is represented by a 2-dimensional Gaussian whose sigma is 5 microradians.

Table 12. L'LORRI Camera Performance Optimistic Case – Degraded Pointing Stability

CCD Format	V-mag 1 x 5s	Orus (days before CA)	Polymele (days before CA)	V-mag 50 x 5s	Orus (days before CA)	Polymele (days before CA)
1x1	15.23	45	46	17.35	137	139
2x2	16.30	78	79	18.42	> 184	> 184
4x4	16.75	98	100	18.87	> 184	> 184

These results show that for Orus and Polymele, it will be possible to use L'LORRI 1x1 CCD format at approximately 45 days prior to the encounter using a single five second exposure even with the “degraded” platform stability case. Using the co-adding technique, it will be possible to use L'LORRI 1x1 mode approximately 137 days prior to each encounter. Based on these results, co-adding is not currently in the baseline navigation plan, since we can meet our delivery requirements by going to 1x1 mode at Encounter – 45 days, but it remains a viable option should detection earlier than 45 days be desired.

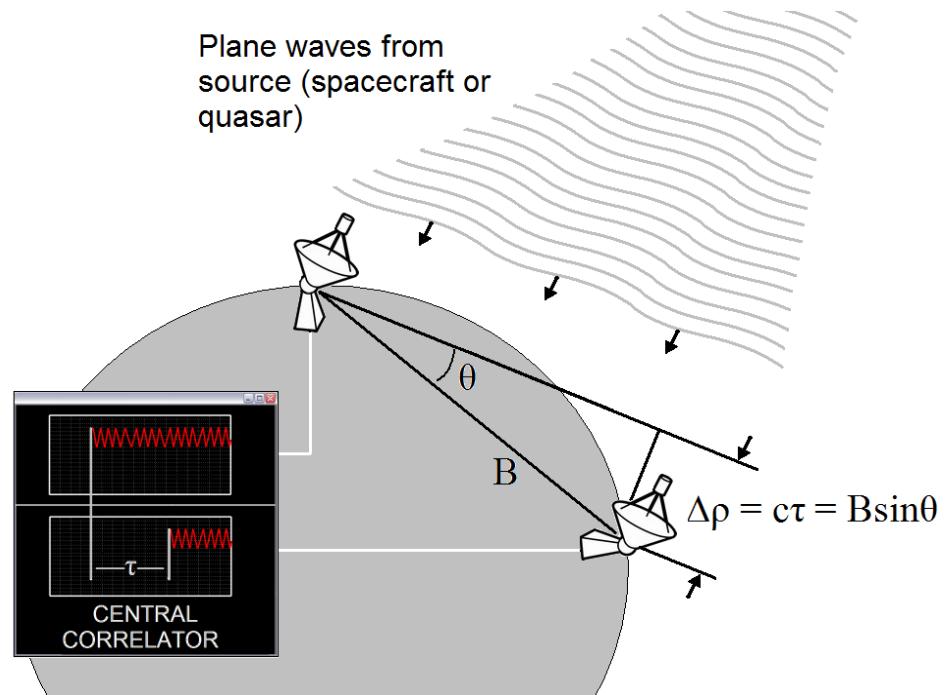
CONCLUSION

The Lucy mission has been described from the point of view of the navigation team. The performance of the L'LORRI camera and the optical navigation systems have been characterized for the most challenging flybys. A covariance analysis was performed by the JPL Solar Systems Dynamics group to provide the navigation team updated covariances using updated assumptions regarding observations of the Trojans from now until the encounters. A covariance analysis was performed for each Trojan encounter using these analyses to characterize the navigation system performance. The 3σ orbit determination delivery, knowledge and reconstruction uncertainties have been presented.

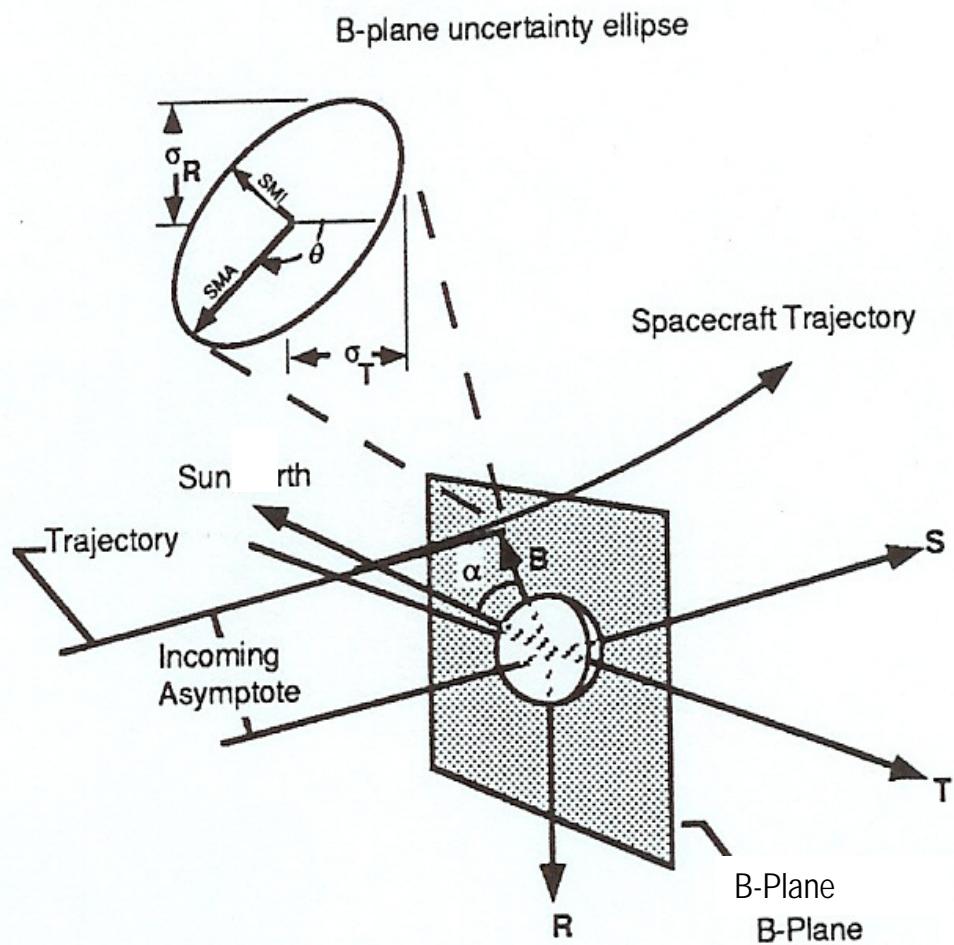
ACKNOWLEDGMENTS

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APPENDIX A: GEOMETRIC DIAGRAM OF DELTA-DIFFERENTIAL ONE-WAY RANGING (DDOR) TRACKING EMPLOYING TWO DSN ANTENNAS



APPENDIX B: THE B-PLANE



APPENDIX C: ACRONYMS AND ABBREVIATIONS

APL	The Johns Hopkins University Applied Physics Laboratory
AU	Astronomical Unit
C/A	Closest Approach
CCD	Charge Coupled Device
DDOR	Delta-Differential One-way Range
DSM	Deep Space Maneuver
DSN	Deep Space Network
EGA	Earth Gravity Assist
FDS	Flight Dynamics System
JPL	Jet Propulsion Laboratory
KXIMP	KinetX Image Processing Tool
L'LORRI	Lucy Long-Range Reconnaissance Imager
MRD	Mission Requirements Document
MVIC	Multi-Spectral Visible Imaging Camera
OD	Orbit Determination
OpNav	Optical Navigation
PSF	Point Spread Function
RTN	Radial, Transverse, Normal
SNR	Signal to Noise Ratio
SWRI	Southwest Research Institute
TCM	Trajectory Correction Maneuver
VLBI	Very Long Baseline Interferometry

REFERENCES

¹ Levison, H. F., et al, "Lucy: Surveying the Diversity of the Trojan Asteroids: The Fossils of Planet Formation," *47th Lunar and Planetary Science Conference*, 2016.

² Hiroi, Takahiro, Zolensky, M. E., Pieters, C. M., "The Tagish Lake Meteorite: A Possible Sample from a D-Type Asteroid," *47th Lunar and Planetary Science Conference*, 2016.

³ Miller, James K., Stanbridge, Dale R., Williams, Bobby G., "New Horizons Pluto Approach Navigation," *14th AAS/AIAA Space Flight Mechanics Conference*, February 2004.

⁴ Taylor, A., Carranza, E., Miller, J., Stanbridge, D., Page, B., Smith, J., Wolff, P., Williams, B., Efron, L., "Earth to Venus 1 Navigation Results For NASA's MESSENGER Mission to Mercury," *17th AAS/AIAA Space Flight Mechanics Conference*, January 2006.

⁵ Williams, K. E., Taylor, A. H., Stanbridge, D. R., Wolff, P., Page, B. R., Williams, B. G. and McAdams, J. V., "Navigation For The MESSENGER Mission's First Mercury Encounter," *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, August 2008.

⁶ Williams, B., Pelletier, F., Stanbridge, D., et al, "Navigation Strategy And Results For New Horizons' Approach And Flyby Of The Pluto System," *AAS/AIAA Astrodynamics Specialist Conference*, August 2015.

⁷ Lucy Project Mission Requirements Document (MRD), DRAFT, March 2017, Lucy-MGMT-REQ-0001, NASA/GSFC.Code 434.